Color reconnection and flow-like patterns in pp collisions

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Increasingly, with the data collected at the LHC we are confronted with the possible existence of flow in pp collisions. In this work we show that PYTHIA 8 produces flow-like effects in events with multiple hard subcollisions due to color string formations between final partons from independent hard scatterings, the so called color reconnection. We present studies of different identified hadron observables in pp collisions at 7 TeV with the tune 4C. Studies have been done both for minimum bias and multiplicity intervals in events with and without color reconnection to isolate the flow like effect.

The understanding of identified particle production in pp collisions is complicated due to the web of processes from the partonic level to the hadronised final state. Phenomenological models are essential to describe the soft regimes of these observables and to gain insight into the underlying physics. So far none of the models has given a satisfactory quantitative explanation of the identified hadron transverse momentum (p_T) spectra at $\sqrt{s} = 0.2$, 0.9, 2.76, and 7 TeV [1–3]. But many interpretations have been offered ranging from coalescence, radial flow, next to leading order calculations (NLO) to the modification of the string tension or the processes incorporated in the various tunes of PYTHIA [4–6].

Although known as the baryon-to-meson puzzle specific to heavy ions the case of the peak in the ratio found in pp collisions has not been satisfactorily explained [7]. However, using the PYTHIA event generator [8] version 8.17 [9] tune 4C [10] we observe a qualitatively good description of the peak as can be seen in Fig. 1, where the preliminary $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio as a function of p_T in pp collisions at 7 TeV measured by ALICE is shown. At high p_T ($p_T > 8$ GeV/c) PYTHIA and NLO [11] agree indicating that this is the fragmentation function regime and in that the ALICE data when they are published can help to constrain the identified fragmentation functions. At low and intermediate p_T (< 8 GeV/c) we observe that the data and PYTHIA show an enhancement of the ratio while NLO calculations behave completely different. This suggests that in addition to the pure fragmentation and non perturbative processes there are other effects contained in PYTHIA that produces this effect. Therefore we decided to understand the origin of this phenomenon in PYTHIA 8 despite the fact that the simulations does not fully explain the data. The inves-

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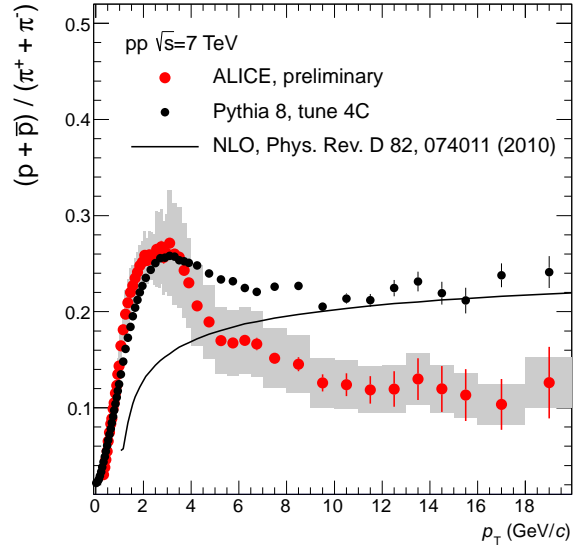† Also at Benemérita Universidad Autónoma de Puebla, Puebla, México

FIG. 1. (Color online) Proton to pion ratio from pp collisions at $\sqrt{s} = 7$ TeV. ALICE data are compared to results from PYTHIA 8 Tune 4C, as well as NLO QCD calculation.

tigation brought to light a so far not recognized feature: a flow-like pattern in the hadron final state attributed to color reconnection (CR) [12]. This finding can give a better understanding of pp collisions, and it can perhaps provide insight into the similar physics region in heavy ion collisions where an even larger proton-to-pion ratio is observed.

In hadron-hadron interactions it is possible to have multiple parton-parton interactions in the same event, because beam-particles contain a multitude of partons which can interact. This is expected to happen in most hadronic collisions at high energies, because for example in pp collisions at LHC energies the inclusive jet cross section for p_{Tmin} below $\approx 4 - 5$ GeV exceeds the total
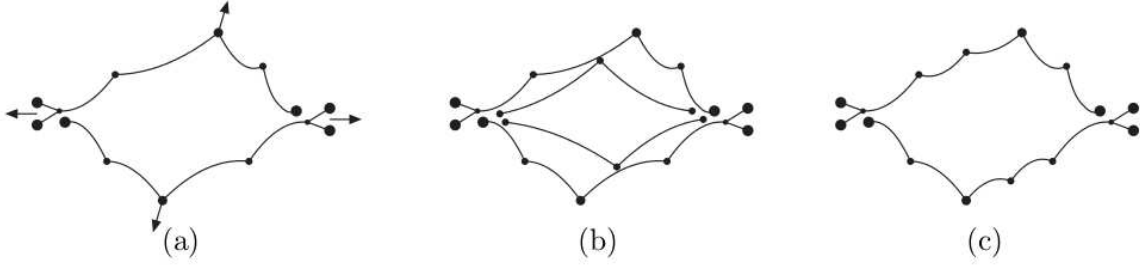
FIG. 2. Illustration of the color reconnection in the string fragmentation model (picture taken from [13]). The outgoing gluons color connected to the projectile and target remnants (a). The second hard scattering (b). Color reconnected string(c).

cross section [14]. The inclusion of multi-parton interactions (MPI) has been supported by many experimental results [15–17]. This is an important assumption used in PYTHIA [8, 18] which allows to have a qualitatively good description of the multiplicity distributions as well as the correlation of observables like transverse sphericity with multiplicity in MB pp collisions at the LHC energies [19].

In PYTHIA, the final step at parton level before the hadronization is the CR, which can affect the hadronization of a many-parton system in a single event with multiple hard subcollisions [20–22]. Fig. 2 shows a sketch of CR in the string fragmentation model where one sees that in a hard parton-parton subcollision the outgoing partons will be color-connected to the beam remnants (2a), a second hard scattering would naively be expected to give new strings connected to the remnants (2b). The assumption of independently fragmenting hard-scattering systems produces a multiplicity which is not in agreement with data. Color reconnection is implemented in such a way that the total string length becomes as short as possible (2c) [13]. Therefore, the fragmentation is not independent and produces the rise of $\langle p_T \rangle$ with multiplicity. However there is another feature of the model which is for the first time discussed here. In general in PYTHIA one string connecting two partons follows the movement of the partonic endpoints. The effect of this movement is a boost of the fragments from the string. The closer the partons are moving in space the bigger the boost. One can think of a boost as a mass effect, for example a boost in the longitudinal directions can be written as $p'_z = \beta\gamma m$, in the rest frame. Without CR for a parton being "knocked out" at mid-rapidity the other string end will be part of the remaining proton moving forward so the boost is small. With color reconnection (CR) 2 partons from independent hard scatterings at mid-rapidity can color reconnect and make a large boost. Therefore color reconnection can create a flow-like effect.

In order to pin down the effect, we calculated different baryon to meson ratios as well as heavy meson to light meson ratios with and without CR. The results were produced using primary charged particles defined as all final particles including decay products except those from weak decays of strange particles. This definition is similar to the one adopted by ALICE [3]. The identified particle yields were computed at mid-rapidity, $|y| < 1$, and the event multiplicity in $|\eta| < 2.4$. The parameter which controls CR is the reconnection range, RR, which enters in the probability to merge a hard scale $\hat{p}_T$ system with one of a harder scale, $(2.085\times\text{RR})^2/((2.085\times\text{RR})^2+\hat{p}_T^2)$. The tune 4C uses the value RR $= 1.5$ which gives a good description of $\langle p_T \rangle$ as a function of multiplicity [10].

Top panel of Fig. 3 shows the $(\text{p}+\bar{\text{p}})/(\pi^++\pi^-)$ ratio in a restricted p_T-interval, $p_T < 6$ GeV/c, for MB (PYTHIA 8 tune 4C) pp collisions at 7 TeV. The distribution shows a clear bump around 2.5 GeV/c. The result for simulations using RR $= 0$ (without CR) indicates a completely different behaviour, for p_T larger than ≈ 1.8 GeV/c the ratio stays flat. Therefore the origin of the peak is attributed to CR. The result also indicates that high p_T particles inside hard jets are not sensitive to color reconnection. The peak is enhanced if one considers events with increased MPI activity. In the figure we plotted the results for events with more than 20 MPI's (proportional to multiplicity), in this case the peak is also pushed up to higher p_T, characteristic effect of flow. The curve crosses the MB curve at $\approx$1.8 GeV/c and the maximum ratio reaches 0.3 at 3 GeV/c. On the contrary, in events with less than 5 MPI's the ratio behaves like in simulations without CR. The evolution of the ratio with the number of MPI's is qualitatively similar to the behaviour of the ratio from peripheral to central Pb $-$ Pb collisions [7]. To study the strength of CR, the bottom panel of Fig. 3 shows the double ratios with and without CR. For $(\text{p}+\bar{\text{p}})/(\pi^++\pi^-)$ and $(\Lambda^0+\bar{\Lambda}^0)/(2\text{K}_s^0)$ one sees a bump at $\approx$ 2.5-3 GeV/c, similar to the one observed in the proton-to-pion ratio (top of the figure). The behaviour of the double ratios indicates that we have a mass effect since the ϕ/π and the $(\text{p}+\bar{\text{p}})/(\pi^++\pi^-)$ ratios exhibit a much larger bump than the $(\text{K}^++\text{K}^-)/(\pi^++\pi^-)$ ratio. Even though in general PYTHIA underestimates the production of strange particles [3, 23], we observe a hierarchy in the effect, it increases with the hadron
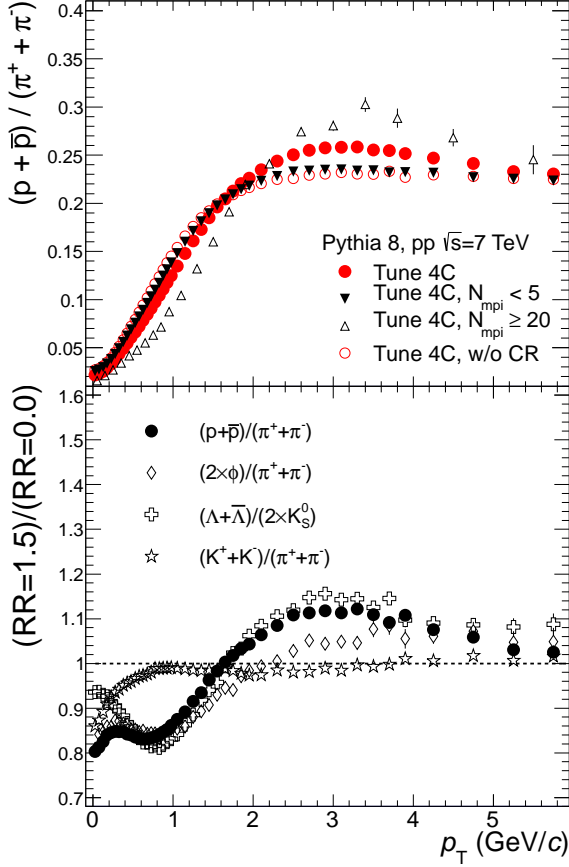
FIG. 3. (Color online) Top panel: $(p + \bar{p})/(\pi^+ + \pi^-)$ as a function of p_T in pp collisions simulated with PYTHIA 8 (solid circles), the ratio for events with low (solid triangles) and high (empty triangles) number of multi-parton interactions are overlaid. Results without color reconnection (RR = 0.0) are also shown (empty circles). Bottom panel: double particle ratios as a function of p_T for different hadron species.

mass, in a pattern reminiscent of the radial flow in heavy ion collisions. Rather than to call it flow since it is not associated to hydrodynamic phenomena, we call it flow-like. We also observe the decrease in the double ratios at higher momenta, a feature that seems to be proper of CR and not of Hydro behaviour.

At LHC energies the CMS Collaboration has published p_T spectra for pions, kaons and protons as a function of the track multiplicity [24]. They found that $\langle p_T \rangle$ for protons increases from ≈ 0.6 GeV/c to ≈ 1.4 GeV/c from their lowest multiplicity class to the highest one. However, the upper panel of Fig. 4 shows that this can only be accommodate by PYTHIA simulations when color reconnection is included. From the plot we observe an increase of $\langle p_T \rangle$ with multiplicity when the color reconnection is turned on, while it looks flatter when color reconnection is turned off. This is the expected behaviour, that is used to tune the amount of CR. However, our work offers an interpretation from a different point of view; with CR the
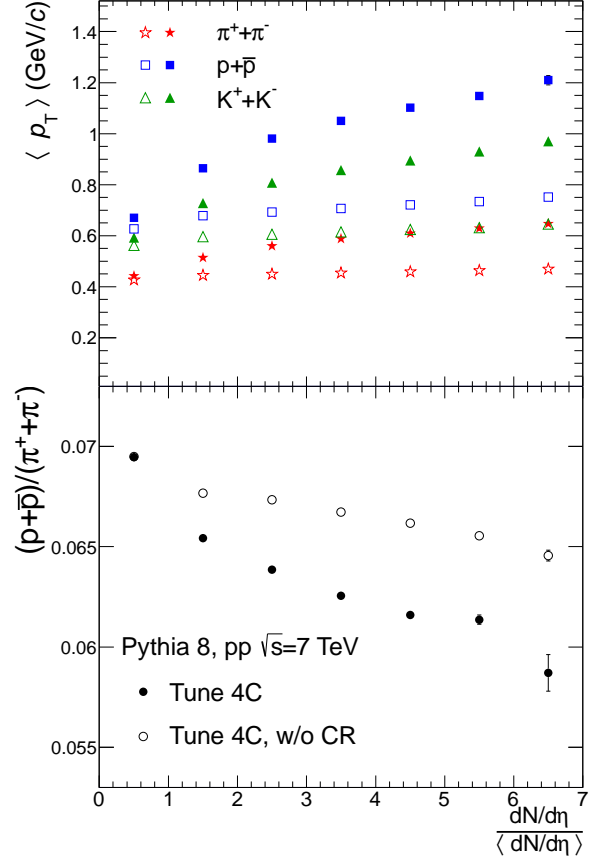

FIG. 4. (Color online) Top panel: mean p_T as a function of the scaled event multiplicity for pions, kaons and protons. Results with CR (solid markers) and without CR (empty markers) are shown. Bottom panel: p_T-integrated proton-to-pion ratio as a function of the scaled event multiplicity.

$\langle p_T \rangle$ of protons increases faster than the pion one *i.e.* the effect increases with the hadron mass. This observation is consistent with the idea of the flow-like effect of string boosts.

We made also a combined fit of the pion, kaon and proton p_T spectra with a blast-wave function. From this fit one can extract the freeze-out temperature, T_{kin}, and the average transverse velocity, $\langle \beta_T \rangle$ [25]. We found in CMS and PYTHIA data a T_{kin}-$\langle \beta_T \rangle$ behaviour as a function of multiplicity very similar to the one observed in heavy ion collisions as a function of centrality [26].

Bottom panel of Fig. 4 shows that the p_T-integrated $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio decreases with the event multiplicity. It is interesting that Pb − Pb data at the LHC exhibits a similar behaviour; a model assuming a baryon-antibaryon annihilation does the qualitatively best description of the trend [26]. In PYTHIA 8 this effect is caused by a change of the particle distribution in the phase space. Actually without any cut on $|y|$ the $\bar{p}/\pi$ ratio stays constant as a function of multiplicity both for with and without CR.

We have demonstrated that the CR scheme used in

PYTHIA 8 event generator exhibits a qualitatively new feature that has a potentially important consequence on our understanding of the details of the pp collisions and possibly beyond, collisions of heavier nuclei. Let us try to summarize here what we think are the implications of this study. For the $(p + \bar{p})/(\pi^+ + \pi^-)$ ratio as a function of p_T (see figure 1) we have shown that even when hard and soft processes are combined, such as in PYTHIA 8, one needs to introduce a flow-like effect to obtain a peak. This suggest that this peak is a direct indicator of a flow-like behaviour, *i.e.*, a "collective phenomena". Similarly we found that $\langle p_T \rangle$ increase with multiplicity in pp especially for heavier particles as observed by CMS, *i.e.*, to be more than just a superposition of individual collisions, we need these collective effects. We are therefore led to believe that hard and soft QCD processes alone are not sufficient to describe the data and one needs to introduce a flow-like effect, *i.e.*, the quoted experimental results show that radial flow is an important effect also in pp collisions.

The color reconnection mechanism warrants in itself further investigations. It produces effects similar to hydrodynamical flow but provides a microscopic picture where the problems of the entropy production and subsequent thermalization are avoided.

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